Euphytica (2006) 150: 281–288
DOI: 10.1007/s10681-006-9119-2 © Springer 2006

Genetic variability for mineral concentration in the forage of Jerusalem artichoke cultivars

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Received 3 November 2005; accepted 31 January 2006

Key words: breeding, genetic variance, *Helianthus tuberosus*, livestock feed

Summary

One of the potential uses of Jerusalem artichoke (*Helianthus tuberosus* L.) is as a forage crop. Information on inherent differences in forage nutritional quality is essential if the quality of the forage is to be improved through breeding. The objectives of this study were to determine the genotypic variability among and within forage of Jerusalem artichoke cultivars for the concentration of N, P, Ca, Mg, K and the Ca/P ratio at flowering, to determine if selection among and within cultivars is feasible, to estimate the magnitude of the genotype × environment interaction, and to examine the relationships among mineral concentrations in the forage. Ten cultivated Jerusalem artichoke cultivars grown in an irrigated field nursery at Bushland, TX were evaluated for N, P, Ca, Mg, K, and the Ca/P ratio in the forage at flowering over a 2-yr period. Cultivars, cultivar × year, and error variances were estimated to calculate the phenotypic variance. Estimates of the within-population variances were also determined. The adequacy of Jerusalem artichoke forage at flowering for maintenance of a ruminant animal was classified as follows: N, Ca, Mg, K as adequate, P inadequate, and the Ca/P ratio as excessive. There were genotypic differences among the ten cultivars for N, P, Ca, Mg, K, and the Ca/P ratio for both years and averaged across years. The magnitude of the genotypic variance components indicated that a substantial proportion of the total variation for these elements was due to cultivar, indicating the possibility of improving these elements. However, further studies on heritability and response to selection will be required before conclusions can be reached concerning the likelihood of successfully breeding for these traits.

Introduction

Jerusalem artichoke (*Helianthus tuberosus*), a perennial sunflower species native to North America, is often present as a weed in pastures (Crawford et al., 1969) and crops (Wyse et al., 1986; Wall et al., 1986) in the USA. Plants are regenerated from rhizomes (tubers) that can persist in the soil, sometimes making their control in subsequent crops more difficult. Jerusalem artichoke has been used as a suitable livestock feed since the mid-1600s, especially in Europe (Cosgrove et al., 2000; Youngen, 1992; Kosaric et al., 1984). It also has been evaluated as a potential biomass crop (Swanton and Cavers, 1989) and as an alternative low-calorie sweetener storing carbons as linear fructose polymers (fructans) and inulin (Schittenhelm, 1999; McLaurin et al., 1999). Promotional claims have been made concerning the North American Jerusalem artichoke crop as a livestock feed, but only meager information is available concerning its nutritional value and the variability of nutrients among and within cultivars.

Jerusalem artichoke forage has the potential to replace or be a substitute for other annual and perennial forages for ruminants. The perennial growth habit would allow for reduced inputs compared to an annual forage system. It could also be grown on erodable soils providing a perennial cover crop. The production of Jerusalem artichoke forage does not require particularly high soil fertility to produce acceptable yields (Cosgrove et al., 2000).

Crawford et al. (1969) rated Jerusalem artichoke forage from fair to excellent for grazing livestock in the Ozark mountain regions of the USA. Dry matter forage yields of 3.0 to 9.9 mg ha^{-1} have been reported by Kosaric et al. (1984) for Jerusalem artichoke cultivars. Seiler (1993) reported forage yields of Jerusalem artichoke cultivars at flowering varied from 3.0 to 6.3 mg ha^{-1}.

If Jerusalem artichoke is to be used as a silage/forage crop, nutritional information about whole plants is essential. The Jerusalem artichoke cultivars evaluated in the current study have been evaluated for their in vitro digestible dry matter (IVDDM) (Seiler, 1993). IVDDM of the cultivars varied from 542 to 715 g kg^{-1} in whole plants at flowering. Most conventional forages have IVDDM concentration between 500 and 800 g kg^{-1} (Tilley & Terry, 1963). All cultivars had IVDDM concentrations above this acceptable level (540 g kg^{-1}) which would produce a moderate gain for growing ruminants (National Academy of Sciences, 1981, 1985, 2000, 2001). Both crude protein and digestible protein concentration are low in Jerusalem artichoke forage compared to high quality forage such as alfalfa (*Medicago sativa*), but Jerusalem artichoke forage is superior in total digestible nutrients (TDN) compared to many perennial grass forages, but it has less TDN than corn (*Zea mays*) silage (Cosgrove et al., 2000). Although Jerusalem artichoke forage has a fiber and lignin content that is higher than corn, it is still palatable to ruminants (Stauffer et al., 1975). The quality of Jerusalem artichoke forage makes it suitable livestock feed, but the forage quality has no advantage over other forage crops and would be classified as a maintenance forage (Cosgrove et al., 2000).

Seiler (1988) reported that whole plant forage of Jerusalem artichoke cultivars had a crude protein of 60 to 102 g kg^{-1}. This would be adequate to maintain dairy cattle which require 80 to 95 g kg^{-1} (National Academy of Sciences, 2001), beef cattle which require 60 to 90 g kg^{-1} (National Academy of Sciences, 2000), sheep which require 94 to 113 g kg^{-1} (National academy of Sciences, 1985), and goats which require 100 to 120 g kg^{-1} (National Academy of Sciences, 1981).

Recommended mineral concentrations in forages for ruminants vary by age, sex and physiological condition of the animal (National Academy of Sciences, 1981, 1985, 2000, 2001). Nutritionally adequate amounts of Ca (2 to 8.8 g kg^{-1}), Mg (1 to 2.1 g kg^{-1}) and K (5.1 to 10 g kg^{-1}) were present in whole plants at flowering, but the P concentration was suboptimal ($<$2 g kg^{-1}) for beef cattle, dairy cattle, sheep, and goats (National Academy of Sciences, 1981, 1985, 2000, 2001).

Seiler and Campbell (2004) concluded that there were genotypic differences among nine populations of wild Jerusalem artichoke for N, P, Ca, Mg and the Ca/P ratio. The magnitude of the genotypic variance components indicated a substantial proportion of the total variance for these elements was due to the genotype, indicating the possibility of improvement through hybridization and selection. Within-population variation for N, Ca, and K was high, indicating potential for improvement with further selection within populations. Population variance for P and Mg was low, suggesting that it would be difficult to improve these minerals through selection.

The existence of genetic variability in mineral element concentrations would indicate the potential for selecting enhanced forage quality. Limited information is available about the genetic variability for the concentrations of key elements (Seiler, 1988; Somda et al., 1999; Seiler & Campbell, 2004), but no information is available on the heritability of these elements and the potential to breed for specific elements in cultivated Jerusalem artichoke cultivars. The objectives of this study were: (i) to determine the genotypic variability among and within forage of Jerusalem artichoke cultivars for the concentration of N, P, Ca, Mg, K, and the Ca/P ratio at flowering, (ii) to determine if selection among and within cultivars is feasible, (iii) to estimate the magnitude of genotype $\times$ environment interaction effects, and (iv) to examine relationships among mineral concentrations in the forage.

Materials and methods

Ten cultivars of Jerusalem artichoke, a summer perennial, were established by planting rhizomes (tubers) in a nursery at Bushland, TX, on Pullman clay loam soil between 1980 to 1981 (Table 1). The cultivars were obtained from the USDA-ARS North Central Regional Plant Introduction Station (NCRPIS) sunflower germplasm collection, Ames, Iowa, USA. The nursery was fertilized with 56 kg N ha^{-1} in the spring of each year. Plants were furrow irrigated to maintain maximum plant growth. The experimental design was a randomized complete block with three replicates. Plots were 1.5 by 7.5 m with a plant population of 50 plants plot^{-1} (45 000 plants ha^{-1}). Weeds were controlled mechanically and by hand-hoeing.

Table 1. Jerusalem artichoke cultivars examined for mineral elements

Cultivar	PI Number	Origin
Sunchoke	—	Turlock, CA, USA
Columbia	—	Morden, MB, Canada
Hybrid 120	357297	Leningrad, FSU
Nakhodka	357300	Leningrad, FSU
Kiev White	357298	Leningrad, FSU
White Crop	357304	Leningrad, FSU
Vadim	357302	Leningrad, FSU
Skorospelka	357301	Leningrad, FSU
Leningrad	357299	Leningrad, FSU
Volga-2	357303	Leningrad, FSU

Jerusalem artichoke plants are branched and multi-headed, and flower over several weeks; thus the flowering stage was defined as the time when one-half of the heads in a plot were flowering (at anthesis). This is equivalent to the R-5.5 stage in cultivated sunflower (Schneiter & Miller, 1981).

Herbage of nine plants per plot was hand-harvested at ground level at flowering in 1983 and 1984. Forage samples were dried in a forced air oven at 65 °C for 48 h, ground in a Wiley mill to pass through a 1-mm screen, and stored in sealed plastic vials prior to chemical analysis for N, P, K, Ca, Mg and calculation of the Ca/P ratio.

Total N was determined by the Kjeldahl method (Jackson, 1958). A nitric, perchloric, and sulfuric acid (3:1 v/v) digestion of 1 g of forage sample preceded analysis for K, Ca, Mg, and P (Jones & Steyn, 1973). Potassium, Ca, and Mg were determined by atomic absorption spectrophotometry (Isaac & Kerber, 1971), and P by the aminonaphthosulfonic acid method on an auto analyzer (Technicon Corporation, 1968). Samples for K, Ca, and Mg were prepared in 0.1% lanthanum (La) prior to analysis (Hanlon, 1992).

Two hundred-seventy samples (9 plants ×3 replicates ×10 cultivars) were analyzed for mineral content each year. The mean value for the plants in a plot was used in an analysis of variance (ANOVA) for each year and across years to determine cultivar differences and the significance of the cultivar × year interactions. Cultivars, replications, and years were considered to be random effects. Variances due to cultivars (σ_g^2), the interaction of year and cultivar (σ_{gy}^2), and error (σ_e^2) and their standard errors were calculated from the mean squares of the ANOVAs, using standard methods (Becker, 1984). The phenotypic variance (σ_P^2) was calculated using the following equation:

$$\sigma_p^2 = \sigma_g^2 + \sigma_{gy}^2 + \sigma_e^2$$

Estimates of within-cultivar variances (σ_W^2) were determined for N, P, K, Ca, Mg, and the Ca/P ratio. An ANOVA was conducted for all cultivars within a year using the individual plant data. One cultivar was then deleted and the ANOVA was repeated on the modified data set. The within-cultivar sum of squares for the deleted cultivar was determined by subtracting the within-cultivar sum of squares of the deleted data set from the within-cultivar sum of squares of the complete data set. The within-cultivar variance for the deleted cultivar was determined by dividing the within-cultivar sum of squares by the within-cultivar degrees of freedom. This process was repeated for all 10 cultivars for both years for a total of 20 ANOVAs for each mineral element. Pearson correlation coefficients were determined among pairs of elements using individual plant data from both years.

Results

Variation among cultivars

There were genotypic differences among the cultivars of Jerusalem artichoke for forage N and K concentrations (Table 2). When averaged across years, cultivar × year (C × Y) interactions were nonsignificant for N and K, indicating that cultivars had similar ranking in both years. There were also genotypic differences among the cultivars for P, Ca, Mg, and the Ca/P ratio for both years and averaged across years. When averaged across years, there was a significant C × Y interaction; i.e., the cultivars did not rank similarly in P, Ca, Mg, and the Ca/P ratio over the two years.

The mean and range of values for the forage mineral element concentrations of the individual plants for 1983 and 1984 are summarized in Table 3. Nitrogen ranged from 8.0 to 17.8 g kg^{-1}, averaging 12.5 g kg^{-1}. Phosphorus had a very narrow range, varying only from 1.0 to 2.5 g kg^{-1}, with an average of 1.6 g kg^{-1}. Calcium had the highest concentration of any element, averaging 21.2 g kg^{-1}, and varying from 10.8 to 32.3 g kg^{-1}. Magnesium had a very narrow range varying from 1.7 to 2.6 g kg^{-1}, averaging 2.2 g kg^{-1}. Potassium averaged 18 g kg^{-1}, ranging from 7.8 to

Table 2. Summary of analysis of variance for mineral element concentrations of Jerusalem artichoke cultivars grown at Bushland, TX, in 1983 and 1984

Mineral element	Statistical significance of mean squares: Cultivars 1983	1984	Across years	C × Y[a] Across years
N	**[b]	**	**	NS[c]
P	**	**	**	**
Ca	**	**	**	**
Mg	**	**	**	**
K	**	**	**	NS
Ca/P	**	**	**	**

[a]C × Y = Cultivar × year interaction effect.
[b],**Indicates significance at the $P = 0.01$ level of probability based on F-test.
[c]NS = Not significant at $P = 0.05$ based on F−test.

29.7 g kg^{-1}. The Ca/P ratio in Jerusalem artichoke forage was high, ranging from 7.7 to 26.7, averaging 14.1 g kg^{-1}.

The among-cultivar genetic variance components (σ_g^2) for P and Mg were small, but accounted for the largest portion of the total phenotypic variance (σ_p^2) overall (Table 4). The genetic variance for all other elements was much higher, with the highest for Ca with 24.2. The ratio σ_g^2/σ_p^2 (genotypic to phenotypic variance) provided an estimate of the proportion of the total variation attributable to cultivar or genetic effects. The σ_g^2/σ_p^2 ratio was greater than 0.91 for N, P, Ca, Mg, K, and the Ca/P ratio (Table 4). The σ_{gy}^2 effect for all elements was low to nonexistent.

Variation within cultivars

The variance among plants within cultivars (σ_w^2) was determined for each cultivar in each year for N, P, Ca, Mg, K, and the Ca/P ratio (Table 5). There were substantial differences among cultivars for within-cultivar variability for N, Ca, and K. However, the within-cultivar genetic variability among cultivars was similar for the two years. Cultivar ‘White Crop’ had the highest within-cultivar variability for N and K in both years. The highest within-cultivar variability for Ca and the Ca/P ratio was in cultivar ‘Leningrad’ in both years. Phosphorus, which was low in the forage, has a very low within-cultivar component making its improvement in a breeding program difficult. The σ_w^2 for Mg was also low, but Mg is adequate in Jerusalem artichoke forage, so there would be no need to specifically select for this element.

Interrelationships of elements

Phosphorus was significantly and positively correlated with N and K, and negatively with the Ca/P ratio, while K was negatively correlated with the Ca/P ratio (Table 6). Nitrogen was significantly and negatively correlated with Ca, Mg, and the Ca/P ratio, and positively and significantly with K. Calcium was significantly and positively correlated with Mg, K, and the Ca/P ratio and not correlated with P.

Discussion

Recommended mineral concentrations in forages for ruminants vary by age, sex and physiological condition

Table 3. Mean and range of values of individual plants for mineral element concentrations and the Ca/P ratio in forage of cultivated Jerusalem artichoke cultivars grown in Bushland, TX, in 1983 and 1984

Mineral element	1983 X̄± SE	1983 Range	1984 X̄± SE	1984 Range	Overall X̄
			g kg^{-1}		
N	12.4 ± 0.1	8.0–17.7	12.6 ± 0.1	8.3–17.8	12.5
P	1.6 ± 0.1	1.0–2.5	1.6 ± 0.1	1.0–2.5	1.6
Ca	20.7 ± 0.3	10.8–30.7	21.7 ± 0.3	11.2–32.3	21.2
Mg	2.1 ± 0.1	1.7–2.6	2.2 ± 0.1	1.8–2.6	2.2
K	18.0 ± 0.2	7.8–26.5	18.1 ± 0.2	12.8–29.7	18.0
			Ratio		
Ca/P	14.0 ± 0.3	7.7–26.4	14.2 ± 0.3	7.7–26.7	14.1

Table 4. Variance components for mineral element concentrations and the Ca/P ratio in forage of Jerusalem artichoke cultivars from the across-years ANOVA

Mineral element	Variance components[a] ± SE[b]				
	σ_g^2	σ_{gy}^2	σ_e^2	σ_p^2	σ_g^2/σ_p^2
N	5.86 ± 2.28	0.00 ± 0.0	0.42 ± 0.01	6.28	0.93
P	0.12 ± 0.05	0.00 ± 0.0	0.01 ± 0.00	0.13	0.92
Ca	24.21 ± 9.42	0.02 ± 0.0	1.08 ± 0.05	25.31	0.96
Mg	0.10 ± 0.02	0.00 ± 0.0	0.01 ± 0.00	0.11	0.91
K	15.31 ± 5.95	0.00 ± 0.0	0.74 ± 0.02	16.05	0.95
Ca/P	29.25 ± 11.37	0.00 ±0.0	0.04 ±0.00	29.29	0.99

[a]σ_g^2 = variance due to cultivar; σ_{gy}^2 = variance due to interaction of year and cultivar; σ_e^2 = error variance; $\sigma_p^2 = \sigma_g^2 + \sigma_{gy}^2 + \sigma_e^2$ = phenotypic variance.
[b]SE of 0.00 indicates SE was < 0.005.

Table 5. Within-population variation (σ_w^2) for ten cultivars of Jerusalem artichoke

Year/cultivar	N		P		Ca		Mg		K		Ca/P	
	$\bar{X}$	σ_w^2	$\bar{X}$	σ_w^2	$\bar{X}$	σ_w^2	$\bar{X}$	σ_w^2	$\bar{X}$	σ_w^2	$\bar{X}$	σ_w^2
	$g\,kg^{-1}$										Ratio	
1983												
Sunchoke	14.2c[a]	0.51	1.5d	0.01	11.8g	0.27	1.8e	0.01	15.2g	0.41	7.8i	0.01
Columbia	14.6b	0.54	1.4e	0.01	16.8f	0.55	2.3a	0.01	21.1b	0.78	12.0e	0.02
Hybrid 120	12.8d	0.41	1.6c	0.01	17.7e	0.61	2.0d	0.01	16.4d	0.47	11.0f	0.01
Nakhodka	9.8f	0.24	1.8b	0.006	18.4d	0.66	2.2bc	0.007	14.0h	0.34	10.3h	0.01
Kiev White	14.2c	0.51	1.8b	0.007	23.8c	1.10	1.8e	0.01	20.9b	0.76	13.6d	0.02
White Crop	15.8a	0.63	2.3a	0.01	23.6c	1.08	2.2c	0.01	26.8a	1.26	10.4g	0.01
Vadim	13.0d	0.43	1.4e	0.004	18.4d	0.66	1.9e	0.01	15.7f	0.43	13.6d	0.02
Skorospelka	10.9e	0.30	1.2f	0.003	23.6c	1.08	2.3b	0.01	17.3c	0.53	19.8b	0.04
Leningrad	9.5f	0.23	1.1g	0.003	27.9a	1.52	2.4a	0.01	15.9ef	0.45	26.0a	0.07
Volga 2	9.0g	0.21	1.6c	0.006	24.5b	1.17	2.2	0.01	16.1de	0.46	15.5c	0.03
1984												
Sunchoke	14.4c	0.43	1.6d	0.004	12.3g	0.32	1.9e	0.007	15.4f	0.50	7.9i	0.01
Columbia	14.9b	0.47	1.5e	0.004	17.6f	0.65	2.4a	0.01	21.4b	0.96	12.2e	0.03
Hybrid 120	13.0d	0.36	1.7c	0.005	18.6e	0.73	2.1d	0.008	16.6d	0.58	11.6f	0.03
Nakhodka	9.9f	0.21	1.8b	0.006	19.3d	0.78	2.3b	0.01	14.2g	0.42	10.4h	0.02
Kiev White	14.4c	0.44	1.8b	0.006	25.0c	1.32	1.9e	0.007	14.2b	0.94	13.8d	0.04
White Crop	16.0a	0.54	2.3a	0.001	24.7c	1.29	2.3b	0.009	27.1a	1.56	10.6g	0.02
Vadim	13.3d	0.37	1.4f	0.003	19.3d	0.79	1.9e	0.007	15.8ef	0.53	13.8d	0.04
Skorospelka	11.1e	0.26	1.2g	0.003	24.7c	1.29	2.4a	0.01	17.5c	0.65	20.1b	0.08
Leningrad	9.7f	0.20	1.1h	0.003	29.3a	1.80	2.4a	0.01	16.1de	0.55	26.4a	0.14
Volga 2	9.2g	0.17	1.6d	0.005	25.8b	1.39	2.2c	0.01	16.1de	0.56	15.6c	0.05

[a]Means in a column followed by different letters are statistically different at $P = 0.05$ according to Duncan's Multiple Range Test.

of the animal (National Academy of Sciences, 1981, 1985, 2000, 2001; Reid & James, 1985). In terms of mineral requirements for the maintenance of a ruminant animal, forage of Jerusalem artichoke cultivars harvested at flowering can be classified as adequate for the following elements: N (9.6 to 14.4 $g\,kg^{-1}$), Ca (2 to 8.8 $g\,kg^{-1}$), Mg (1 to 2.1 $g\,kg^{-1}$), and K (5.1 to 10 $g\,kg^{-1}$), while P (2 $g\,kg^{-1}$) is inadequate, and the

Table 6. Correlation coefficient (r) of mineral element concentrations and the mineral element Ca/P ratio in forage of ten cultivars of Jerusalem artichoke harvested at flowering on the basis of data combined for two years[a]

Mineral element	P	N	Ca	Mg	K
N	0.49**,b				
Ca	−0.01ns	−0.33**			
Mg	−0.08ns	−0.29**	0.47**		
K	0.61**	0.71**	0.29**	0.18**	
Ca/P	−0.65**	−0.55**	0.75**	0.44**	−0.16**

[a] $n = 540$ for all elements.
[b] **Indicates significance at the $P = 0.01$ levels of probability; ns = nonsignificant.

Ca/P ratio is high (>7:1). This was also true for wild Jerusalem artichoke populations examined by Seiler and Campbell (2004).

Rations with the most efficient utilization of Ca and P by ruminants are those with a Ca/P ratio between 1:1 and 2:1. When this ratio exceeds 7:1, metabolic disorders may arise (National Academy of Sciences, 1981, 1985, 2000, 2001). The high Ca/P ratio ($\bar{X} = 14{:}1$) in Jerusalem artichoke forage results from a high Ca concentration and suboptimal level of P. High Ca/P ratios (>7:1) were also observed in wild Jerusalem artichoke populations (Seiler & Campbell, 2004). If Jerusalem artichoke was used as the predominant source of feed, a P supplement or the addition of some other forage with a high concentration of P would be necessary to help reduce the risk of metabolic disorder.

A substantial proportion of the total variation among cultivars for N, Ca, and K is due to genotypic differences. This would indicate the potential for improving mineral concentration through further selection within cultivars. The σ^2_{gy} effect for all elements was low to nonexistent, indicating that the relative concentration of these elements in Jerusalem artichoke was not affected by environment (year). The σ^2_g/σ^2_p ratio was similar to the heritability estimate, but the term heritability is inappropriate because cultivars are not the progeny of a reference population. Nevertheless, the high variance components (>0.90) for all the elements indicate the possibility of selecting for several of the mineral elements. Slightly higher variance components were observed for these elements in wild Jerusalem artichoke populations probably due to the greater genetic diversity in these populations (Seiler & Campbell, 2004).

Most elements in Jerusalem artichoke forage appear to be amenable to improvement by selection among the cultivars. However, P, which is low in forage of Jerusalem artichoke at flowering, has a low cultivar variance component and a narrow range of values, so selection to increase this element would increase the P concentration only slightly. The wild Jerusalem artichoke populations previously examined were also low in P, so they would not be a useful genetic resource to increase P concentration in the forage (Seiler & Campbell, 2004). Magnesium also had a relatively low cultivar variance component and narrow range of concentrations. Since Mg is already adequate in the forage, there should be no specific need to select for this element.

The σ^2_w within-cultivar variance consisted of genetic variability within cultivars, plant-to-plant environmental variation, and experimental error. Comparison of σ^2_w thus provides an indication of the relative heterogeneity within cultivars (Vogel et al., 1989).

Elements, especially N, Ca, and K have larger within-cultivar variability and offer the potential for selection to improve Jerusalem artichoke forage. However, the within-cultivar genetic variability among cultivars varied slightly between the two years. The within-cultivar genetic variation of Jerusalem artichoke cultivars should allow for the selection of individuals for improving mineral elements in the forage.

Again, it appeared as though P, which is low in forage, has a low within-cultivar component making its improvement in a breeding program difficult. The σ^2_w for Mg was also low, but Mg is adequate in the forage, so there is no need to specifically select for this element.

Unfortunately it does not appear feasible to select for increased P concentration to reduce the Ca/P ratio to a less than a 7:1 level. The moderate negative correlation between P and Ca/P ratio ($r = -0.65$) suggests that the Ca/P ratio could be reduced, but at the expense of a reduced P level, which is undesirable. Also, the narrow range of P concentrations and low variability might make selection for increased P levels very difficult. Since there does not appear to be any correlation between Ca and P, and Ca has a high correlation in a favorable direction for selection with the Ca/P ratio, one could reduce the Ca/P ratio by selecting for lower Ca. Selection for lower Ca with its much larger range of concentrations and high variance component would be more feasible than selection for increased P with its narrow range of concentrations and low variance. It is interesting to note that N has a positive correlation with P, and a negative correlation with Ca. This would suggest the possibility of selecting for higher N resulting in a higher P concentration, thus lowering the Ca/P ratio.

The between-cultivar variance (Table 4) and the magnitude of the within-cultivar genetic variance (Table 5) indicate that it should be possible to improve N, Ca, and K concentrations by selecting among and within cultivars. It may be possible to lower the Ca/P ratio by breeding for a lower Ca concentration in the forage, which is already adequate. The variability among the cultivars for Ca concentration and the low genotype $\times$ environment interaction for Ca indicates that this should be possible. However, lowering the Ca/P ratio by increasing P concentration does not appear to be possible. Due to the positive correlation between N and P, but negative correlation with Ca, it may be possible to select for higher N, thus somewhat decreasing the Ca/P ratio.

The magnitude of the genotypic variance components indicated that a substantial proportion of the total variations for N, Ca, and K was due to cultivar, indicating the potential for improvement of these elements through breeding and selection. However, it should be pointed out that the current study only indicated the potential for selecting for these elements. Additional studies on heritability and response to selection will be required before conclusions can be reached concerning the likelihood of successfully breeding for improved mineral concentrations in Jerusalem artichoke forage.

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